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Rotorcraft Handling Qualities and Flight Control System Specification Personal Computer Tutorial and Data Base

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Project Summary

Rapid ongoing changes in handling qualities evaluation, flight control system design, and flight test technology requires a continuing training program for flight test engineers, and flight test pilots. The demanding schedule of practicing professionals makes it difficult, however, to provide this training in the conventional classroom environment. As a result, these is a need for computerized "self-paced learning" programs to minimize the cost and time of formal instruction and offer more flexibility for on-the-job-training. Modern computer power and programming technology an opportunity to develop such a computer aided learning tool for self-training of aerospace engineers and test pilots on the subjects of flying qualities specifications and control system design. This computer aided engineering training tool will provide a self-paced learning environment and thus satisfy the demanding schedule of these professionals. Due to practical considerations of memory and mass storage, most Personal Computer (PC) tutorial are based on canned scenarios that limit the scope of a student's interaction. Recent advances in network technology have allowed PC's to act as smart terminals and remotely share access to the memory, mass storage and CPU capability of more powerful, UNIX based computers and workstations. These PC's can now even emulate the X-window graphical interfaces of the workstations, allowing their full potential to be accessed at every desk. A tutorial that utilizes the X-Terminal emulation capability of a PC can combine locally based tutorial sessions with remotely accessed data bases, simulations, and analysis utilities, resulting in a powerful desktop learning tool. At the same time, it also provides a valuable computer aided tool for engineers to perform handling qualities evaluation and iterative control system design.

In the Phase I effort of this project, a prototype tutorial was developed on a personal computer to demonstrate the concept of computer aided learning of flying qualities specification and control design with interactive simulation and analysis examples. Through this tutorial, users have desktop interactive access to both a comprehensive flight simulation/analysis program and an instructional learning tool with references cross linked to on-line specifications and background material.

Under the Phase I efforts, we have successfully developed a demonstration prototype tutorial with a PC. The Phase I effort has proved the feasibility of interactive learning with on-line examples of flying qualities specifications, iterative control system design, closed loop flight vehicle simulation, and handling qualities evaluation. The technical objectives under the Phase I effort have been achieved by accomplishment of the specified tasks. These tasks included implementation of a set of handling qualities analysis functions; integration of control system design and analysis utilities;

networking of a PC with a UNIX host workstation where the comprehensive flight simulation and analysis program (FLIGHTLAB) is installed, designing and prototyping of a flying qualities tutorial.

Introduction

It is essential to have a continuing training program for updating handling quality and flight test engineers, and flight test pilots with ongoing changes in flying qualities specifications, flight control system design, and flight test technology. The demanding schedule of these practicing professionals makes it difficult to attain the training from a conventional classroom environment. A computer aided tutorial is an efficient tool to provide this self-learning in a cost effective way. It offers flexibility for on-the-job training and is also a valuable analysis tool. With today's computer power and modern programming technology, an interactive presentation of the training materials is straightforward. The text, figures, and mathematical equations can all be displayed with textbook quality. A computer tutorial typically follow the lesson plan of a formal training class, but with interactive examples to facilitate learning by active involvement of the students. Due to its low cost and easy maintenance, a PC is readily available to all professional at the office and at home. Although there are still limitations in the PC's memory and computational power, recent advances in network technology have allowed PC's to act as smart terminals and remotely access more powerful, UNIX based computers and workstations. Today's PC can even emulate the X-window graphical interfaces of the workstations. A tutorial that utilizes the X-Terminal emulation capability of a PC can combine locally based tutorial sessions with remotely accessed data bases, simulations, and analysis utilities, resulting in a powerful desktop learning tool.

In addition to classroom instruction, students should also gain practical experience through conducting laboratory experiments. Hands-on access to flight vehicles, however, is limited due to cost constraints and safety issues. Interactive simulation can provide "virtual" access to flight vehicles, allowing active participation in planning, conducting and evaluating flight tests without the risk and cost of using actual flight vehicles. On-line computer aided engineering tools for handling qualities evaluation, and flight control system design can also be interactively coupled to the flight simulations to gain experience with the tools and enhance the students' understanding of flight vehicle characteristics. It is desirable, therefore, to augment a programmed instruction course on handling qualities evaluation, flight control system design, and flight test technology with on-line access to computerized simulation and analysis tools to provides a comprehensive learning experience.

FLIGHTLAB, developed by Advanced Rotorcraft Technology, Inc., provides such a computerized simulation and analysis tool to satisfy the need, Ref. [1]. FLIGHTLAB is a software tool for analysis and simulation of a wide range of dynamic, aerodynamic and control systems. Its reconfigurable components and high level modeling templates allow customized simulation model building. Its analysis interface provides interactive generation of customized analysis/test scenarios. FLIGHTLAB's sophis-

ticated rotorcraft simulation can be run in real time using the built-in parallelization capabilities. FLIGHTLAB requires a powerful UNIX based workstation as a host, but it can be accessed by PCs through a network with X-terminal emulation.

In the Phase I, we have developed a prototype tutorial to demonstrate the concept of computer aided learning of flying qualities and control design with interactive simulation and analysis examples. Through this tutorial, users have interactive access to both FLIGHTLAB simulation/analysis environment and an interactive instructional program with references cross linked to on-line specifications and background material. Therefore, the tutorial can be invoked on a PC and connected to the FLIGHTLAB. It can perform the handling qualities parameter evaluation, control system design, and flight simulation under the FLIGHTLAB environment.

Technical Objectives

The goals of the Phase I effort was to proof the concept of the tutorial design and to demonstrate the feasibility through prototype. The goals have been successfully achieved through accomplishment of the specific technical objectives:

1. Development of the prototype tutorial to show the concept of computer aided learning of aircraft handling qualities with interactive simulation and analysis examples.

2. Demonstration of the capability to interactively perform handling qualities evaluations, iterative control system design, and closed loop simulation using comprehensive rotorcraft models under the FLIGHTLAB environment.

Handling Qualities Analysis Tools

The Handling Qualities Analysis Tools performs computer aided handling qualities parameter evaluation and plots the results against the handling qualities specifications. The analysis tools developed under Phase I effort are based on a handling qualities analysis toolkit from the United Kingdom's Defense Research Agency (DRA) in Bedford, England, Ref [2]. The DRA has been heavily involved with the U.S. Army's development of ADS-33C. They have developed a toolkit to perform the handling qualities evaluation in accordance with ADS-33C. The toolkit was designed to operates within the MATLAB environment using basic MATLAB functions as building blocks within individually tailored functions to allow calculation of appropriate flying qualities parameters. Since FLIGHTLAB's high level simulation language, SCOPE,

is based on the MATLAB syntax, porting this toolkit to the FLIGHTLAB environment was a straight forward task. The toolkit contains one function per criterion for calculating the appropriate parameters, together with an associate function for plotting those parameters against ADS-33C requirements.

There are a few functions used by the toolkit that are not directly available in FLIGHTLAB. In Phase I, efforts have been made to develop compatible functions in FLIGHTLAB to support implementation of the toolkit. We have also augmented the FLIGHTLAB plotting capability to fulfill the need of the toolkit plot functions.

The functionality that has been implemented under the Phase I effort is summarized in Table 1.

It should be noted that only the ADS 33C specification on rotorcraft handling qualities has been entered under the Phase I effort. In Phase II, the MIL-H8501 specification for rotorcraft handling qualities, the MIL-F-83300 specification on V/STOL handling qualities, the MIL-F-8785C specification on fixed wing handling qualities and MIL-F-9490 and MIL-F-87242 specifications for flight control systems will be added. The AGARD Report No. 577 on V/STOL handling qualities will also be addressed. The information will be presented as text, tabulated data and figures. this includes handling qualities terminology and definitions, flying qualities requirement and flight test maneuver specification. On-line access to specifications on structural load limit will also be provided.

The increased emphasis on frequency domain methods in flight testing necessitates a better understanding by flight test personnel of the capabilities and limitations of this approach. A recent training course developed by the Army's Airworthiness Qualification Test Directorate (AQTD) covers the planning, execution and analysis of a frequency domain flight test, Ref. [5]. Under the Phase II effort, a section of the self guided tutorial will be developed to address the material in the Army's frequency testing training course.

To illustrate the use of the ADS-33C handling qualities analysis tool, we present the following examples.

The first example is the calculation of the short term bandwidth and phase delay handling qualities parameters from response to a small amplitude control input. To do this, we use the **bandwdth** function that operates on a linearized model such as

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} \tag{1}$$

$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u} \tag{2}$$

where $\boldsymbol{x}$ is the state variable vector and $\boldsymbol{u}$ is the control input vector. The $\boldsymbol{y}$ is the output vector. The $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$ and $\boldsymbol{D}$ are the stability, control, state selection and output matrices.

Table 1: Function Reference

Function	Purpose	ADS-33C Spec (Section)	Filename
bandwidth	Calculate short term bandwidth and phase delay handling qualities parameters from response to small amplitude control inputs	3.3.2.1, 3.3.5.1, 3.4.1.1, 3.4.5.1, 3.4.7.1	bandwdth.fun
damping	Calculate natural frequency and damping ratio handling qualities parameters from the mid term	3.3.2.2, 3.3.5.2, 3.4.1.2, 3.4.8.1	damping.fun
phiosc	Calculates bank angle oscillation handling qualities parameters from the response to small amplitude roll control input	3.4.6.1	phiosc.fun
plotbw	Plot bandwidth and phase delay handling qualities parameters against ADS-33C requirements	3.3.2.1, 3.3.5.1, 3.4.1.1, 3.4.5.1, 3.4.7.1	plotbw.fun
plotdmp	Plot natural frequency and damping ratio handling qualities parameters against ADS-33C requirements	3.3.2.2, 3.3.5.2, 3.4.1.2, 3.4.8.1	plotdmp.fun
plotphi	Plot bank angle oscillation handling qualities parameters against ADS-33C requirements	3.3.6.1	plotphi.fun
plotqck	Plot attitude quickness handling qualities parameters against ADS-33C requirements	3.3.3, 3.3.6, 3.4.5.2	plotqck.fun
plottor	Plot torque response handling qualities parameters against ADS-33C requirements	3.3.10.2	plottor.fun
plottc	Plot turn co-ordination handling qualities parameters against ADS-33C requirements	3.4.6.2	plottc.fun
plotyc	Plot yaw rate due to collective cross-coupling handling qualities parameters against ADS-33C requirements	3.3.9.1	plotyc.fun

Table 2: Function Reference - continued

Function	Purpose	ADS-33C Spec (Section)	Filename
quickness	Calculate attitude quickness parameters from the moderate/large amplitude response to control inputs	3.3.3, 3.3.6, 3.4.5.2	quickness.fun
torque	Define torque response handling qualities parameters from the response to a small amplitude collective control input	3.4.6.2	torque.fun
turnco	Calculate turn co-ordination handling qualities parameters from the response to a small amplitude roll control input	3.4	turnco.fun
vertrate	Obtain equivalent time domain handling qualities parameters from the vertical rate response to a small amplitude collective control input	3.3.10.1, 3.4.3	vertrate.fun
yawcoll	Define yaw rate due to collective cross-coupling handling qualities parameters from the response to a small amplitude amplitude collective control input	3.3.9.1	yawcoll.fun
heqcost	Determine the least squares fit between the actual and equivalent vertical rate time and equivalent vertical rate time responses specified in 'def_flight_path'		heqcost.fun
heqstep	Perform one step of the Nelder-Mead simplex algorithm for minimizing a nonlinear function of several variables		heqstep.fun

For the linearized model, we can generate a frequency Bode plot from the **cfreq** function and then compute the bandwidth and phase delay by calling the **bandwdth** function. An example result for the Puma helicopter roll response bandwidth and phase delay computed from these handling qualities evaluation functions (**bandwdth**) is shown in Fig. 1. The bandwidth and phase delay can also be plotted against ADS-33C requirements using the function **plotbw** , Fig. 2. As it illustrates, the Puma roll response bandwidth only satisfies the Level 3 requirement for the air combat/target acquisition and tracking Mission Task Element (MTE) and Level 2 requirement for all other MTEs. The script that performs the above task is listed in Appendix A as **Script One** for reference.

The second example is the calculation of the natural frequency and damping ratio handling qualities parameters. For this task, a time response needs to be generated first. Of course, the time response can be attained in various ways. In this example, we use the **impulse** function that produces the time response of the helicopter due to an impulse control input. The natural frequency and damping is then computed using the **damping** function. Fig. 3 shows the Puma roll response time history with maxima and minima identified. Finally, the response natural frequency/damping is plotted against the ADS-33C requirements in Fig. 4. The scripts performing the above task is listed in Appendix A as **SCript Two** for reference.

The third example is the calculation of moderate amplitude of roll altitude and rate changes (altitude quickness). For this, the **quickness** function is applied. Fig. 5 shows the Puma helicopter roll response time history with maximum roll rate and bank angle identified. The handling qualities evaluation is then displayed using **plotqck** function, Fig. 6. As shown, the Puma roll response attitude quickness satisfies Level 3 requirement for air combat/target acquisition and tracking mission task elements (MTEs) and borderline Level 1/Level 2 requirement for all other MTEs.

Control System Analysis and Design Utilities

The utilities developed for control system performance analysis and design under the Phase I effort include

1. Algebraic Riccati Equation Solution.
2. Linear Quadratic Regulator
3. Linear Quadratic Estimator
4. Steady State Solution
5. Set-Point Controller

6. Integral-Error Controller

These functions have been integrated into FLIGHTLAB and utilized in the interactive tutorial sessions.

The control system analysis and design utilities operate on the following state space model:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} \tag{3}$$

$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u} \tag{4}$$

where $\boldsymbol{x}$ is the state variable vector, $\boldsymbol{y}$ is the output vector, and $\boldsymbol{u}$ is the input vector. Bold type letters were used for vectors and matrices. In the following, subscripts are used to distinguish among plant models. Models with the subscript of *cl* are closed loop models while ones with *c* are compensators. The subscript *e* is used to mark estimators. $\boldsymbol{Q}$, $\boldsymbol{R}$ and $\boldsymbol{N}$ are used as weighting matrices.

Linear Quadratic Gaussian

The following utilities support control design using Linear Quadratic Gaussian theory, Ref. [8]. All these approaches are based on the solution to the Riccati Equation and require full state feedback. Utilities to generate estimators for unmeasured states are also included.

Algebraic Riccati Equation

The function **ARE** solves an algebraic Riccati equation. The current SCOPE implementation is based on the MacFarlane-Potter method which uses the eigensystem of the Euler-Lagrangian equation.
The function call

$$\boldsymbol{S} = \boldsymbol{ARE}(\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{Q}, \boldsymbol{R});$$

returns $\boldsymbol{S}$ the solution of the algebraic Riccati equation.

$$0 = \boldsymbol{A}^T\boldsymbol{S} + \boldsymbol{S}\boldsymbol{A} + \boldsymbol{Q} - \boldsymbol{S}\boldsymbol{B}\boldsymbol{R}^{-1}\boldsymbol{B}^T\boldsymbol{S}$$

Linear Quadratic Regulator

The function **LQR** is used to design a linear quadratic regulator. A time-invariant optimal feedback gain $\boldsymbol{K}_c$ is found by solving the following minimization problem.

$$\min_{\boldsymbol{u}} J = \frac{1}{2}\int (\boldsymbol{x}^T\boldsymbol{Q}\boldsymbol{x} + \boldsymbol{u}^T\boldsymbol{R}\boldsymbol{u} + 2\boldsymbol{x}^T\boldsymbol{N}\boldsymbol{u})\, dt$$

The famous result of this minimization problem is feeding back a control input signal of

$$\boldsymbol{u} = -\boldsymbol{R}^{-1}\boldsymbol{B}^T\boldsymbol{S}\boldsymbol{x} \triangleq -\boldsymbol{K_c}\boldsymbol{x}$$

where $\boldsymbol{S}$ is solution of the algebraic Riccati equation:

$$0 = \boldsymbol{A}^T\boldsymbol{S} + \boldsymbol{S}\boldsymbol{A} + \boldsymbol{Q} - \boldsymbol{S}\boldsymbol{B}\boldsymbol{R}^{-1}\boldsymbol{B}^T\boldsymbol{S}$$

The function call

$$[\boldsymbol{K}_c, \boldsymbol{e}, \boldsymbol{S}] = \boldsymbol{LQR}(\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{C}, \boldsymbol{Q}, \boldsymbol{R}, \boldsymbol{N});$$

returns the compensator gain $\boldsymbol{K}_c$, the closed loop eigenvalues e, and the Riccati equation solution $\boldsymbol{S}$.

Linear Quadratic Estimator

Consider a linear system with process and measurement noise:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{G}\boldsymbol{w} \tag{5}$$

$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u} + \boldsymbol{v} \tag{6}$$

where $\boldsymbol{w}$ and $\boldsymbol{v}$ are zero-mean process and measurement noise respectively. $\boldsymbol{LQE}$ computes the continuous, steady-state Kalman filter gain of the estimator system given as

$$\dot{\boldsymbol{x}}_e = \boldsymbol{A}\boldsymbol{x}_e + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{L}(\boldsymbol{y} - \boldsymbol{C}\boldsymbol{x}_e - \boldsymbol{D}\boldsymbol{u})$$

where $\boldsymbol{x}_e$ is the estimate of the state.
The function call

$$[\boldsymbol{L}, \boldsymbol{e}, \boldsymbol{S}] = \boldsymbol{LQE}(\boldsymbol{A}, \boldsymbol{G}, \boldsymbol{C}, \boldsymbol{Q}, \boldsymbol{R}, \boldsymbol{N});$$

returns the estimator gain $\boldsymbol{L}$, the eigenvalues of the estimator, $\boldsymbol{e}$, and the solution of the Ricaati equation, $\boldsymbol{S}$. Here the $\boldsymbol{Q}$ is the process noise covariance $(E(\boldsymbol{w}\boldsymbol{w}^T))$, $\boldsymbol{R}$ is the measurement noise covariance $(E(\boldsymbol{v}\boldsymbol{v}^T))$, and $\boldsymbol{N}$ the process and measurement cross-covariance $(E(\boldsymbol{w}\boldsymbol{v}^T))$.

Steady-State Control

While a regulator designed by using **LQR** is used in a stability augmentation system, we need separate automatic control systems to make the system follow a certain non-zero command. This section will introduce two steady-state control logics, a set-point controller and an integral-error controller.

Steady State Solution

For a system with arbitrary number of inputs and outputs, the steady-state solution with command of $\boldsymbol{y}_c$ is found by minimizing

$$J = (\boldsymbol{y} - \boldsymbol{y_c}^T)\boldsymbol{Q}(\boldsymbol{y} - \boldsymbol{y}_c) + \boldsymbol{u}^T\boldsymbol{R}\boldsymbol{u}$$

subject to constraints of

$$\begin{aligned} 0 &= \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} \qquad (7) \\ \boldsymbol{y} &= \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u} \qquad (8) \end{aligned}$$

This minimization problem is the same as minimizing an augmented cost function,

$$J' = (\boldsymbol{y} - \boldsymbol{y_c}^T)\boldsymbol{Q}(\boldsymbol{y} - \boldsymbol{y}_c) + \boldsymbol{u}^T\boldsymbol{R}\boldsymbol{u} + \boldsymbol{\lambda}^T(\boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u}) + \boldsymbol{\mu}^T(\boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u} - \boldsymbol{y})$$

If the number of inputs is greater than or equal to the number of outputs, it is possible to make $\boldsymbol{y}_{ss}$ be the same as $\boldsymbol{y}_c$ by dropping out the first term of J. If the number of outputs is greater than that of the inputs, the steady-state output vector is not the same as $\boldsymbol{y}_c$ and is given as

$$\boldsymbol{y}_{ss} = \boldsymbol{y}_c + \boldsymbol{Q}^{-1}\boldsymbol{\mu}$$

The function call

$$[\boldsymbol{N}_{xy}, \boldsymbol{N}_{uy}, \boldsymbol{N}_{yy}] = SState(\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{C}, \boldsymbol{D}, \boldsymbol{R}, \boldsymbol{Q});$$

returns a set of steady state gain matrices. The steady-state states, inputs, and outputs are then given as

$$\begin{aligned} \boldsymbol{x}_{ss} &= \boldsymbol{N}_{xy}\boldsymbol{y}_c \qquad (9) \\ \boldsymbol{u}_{ss} &= \boldsymbol{N}_{uy}\boldsymbol{y}_c \qquad (10) \\ \boldsymbol{y}_{ss} &= \boldsymbol{N}_{yy}\boldsymbol{y}_c \qquad (11) \end{aligned}$$

Set-Point Controller

A simple output command logic is acquired from hold logic by simply changing the set-point:

$$\boldsymbol{u} - \boldsymbol{u}_{ss} = -\boldsymbol{K}_c(\boldsymbol{x} - \boldsymbol{x}_{ss})$$

Using the results of **SState**, we have a feedback control input of

$$\boldsymbol{u} = (\boldsymbol{N}_{uy} + \boldsymbol{K}_c\boldsymbol{N}_{xy})\boldsymbol{y}_c - \boldsymbol{K}_c\boldsymbol{x}$$

Integral-Error Controller

The set-point controller introduced before is simple but not robust to unmodeled disturbance or modelling errors. Small disturbance or modelling errors can be rejected by using an integral-error controller. The compensator system is augmented with

$$\dot{e} = y - y_c$$

An example of the usage of the integral-error controller was given as follows. The plant model is OH-6A at hover. Figure [5] shows the forward velocity response and the longitudinal cyclic control history for a command input of $u = 10 ft/sec$. The scripts perform the job is given in Appendix A listed as **Script Three** for reference.

Simulation of Flight Test Scenarios and Data Base

Under the Phase I effort, ART has developed a series of test scenarios and data reduction/formatting techniques that can be performed on FLIGHTLAB simulations as well as flight test data. These tests are performed to determine the performance and stability characteristics of rotorcraft. The design of the tests are derived from the specifications in U.S. Navy Test Pilot School Manuals, Refs. [3-4]. The simulation of the test scenarios implemented under Phase I include:

1. **Hover Performance**: The weight of the model or the rotor RPM is varied and a plot of engine power required versus thrust is generated.

2. **Climb Performance**: The collective control is varied from its trim condition at the maximum rate of climb airspeed and the vertical flight path angle that results in trimmed flight for the collective setting is computed. The resulting climb rate is plotted versus collective setting.

3. **Autorotative Descent Performance**: The engine is disengaged and the rotorcraft is trimmed for a range of airspeeds using vertical flight path angle as the trim variable to maintain constant rotor RPM at a desired setting. The resulting rate of descent is plotted versus airspeed.

4. **Level Flight Trimmed Controls**: The roll and pitch attitudes along with the four control settings required to trim the aircraft in level flight from 40 to 160 knots are attained and plotted against airspeed.

5. **Low Speed Flight**: The roll and pitch attitudes along with the four control settings required to trim the aircraft in low speed forward and rearward flight are attained and plotted against airspeed (-40 to 40 Knots).

6. **Sideward Flight**: The sideslip angle required to trim at zero roll angle for sideward flight is determined and the pitch angle and flight controls are plotted against sideslip angle.

7. **Longitudinal Static Stability**: The rotorcraft is trimmed for straight and level flight at a specified airspeed and the longitudinal control is varied from the trim position with collective fixed. The vertical flight path angle is then used to trim the vehicle for the longitudinal stick position and the resulting airspeed is plotted versus longitudinal stick position to display the longitudinal static stability.

8. **Lateral Static Stability**: The rotorcraft is trimmed for straight and level flight at a specified airspeed and the lateral control is varied from the trim position with roll angle held constant. The sideslip angle is then used to trim the vehicle for the longitudinal stick position and the resulting lateral airspeed is plotted versus lateral stick position to display the lateral static stability.

9. **Longitudinal Maneuver Stability**: The rotorcraft is trimmed for straight and level flight at a specified airspeed and the longitudinal control is varied with collective control fixed to trim the rotorcraft to a specified normal acceleration. The resulting control positions are plotted versus normal acceleration to display the longitudinal maneuver stability.

10. **Lateral Maneuver Stability**: The rotorcraft is trimmed to a range of specified normal accelerations for coordinated turns at a specified airspeed using heading rate as the trim variable and the resulting control positions are plotted versus normal acceleration to display the lateral maneuver stability.

11. **Critical Azimuth**: The rotorcraft is trimmed to hover and a wind of specified magnitude is varied in direction from 0 to 360 degrees. The control settings required to trim the vehicle at each wind azimuth are then plotted against the wind azimuth to display the critical azimuth data.

12. **Dynamic Stability**: Time response for steps, doublets, and pulses from trim in each control axis are obtained at specified airspeeds and plotted to display the dynamic stability.

To support organization of the extensive data produced from both flight simulation and flight test, a data base management system has been added to FLIGHTLAB. This data base allows users to store and retrieve the modeling data with reference to the model and simulation conditions under which the data was generated. The flight test data can also be stored for analysis. The flight test data can be used for simulation

comparison. They can be also used in connection with model validation analysis utilities such as parameter identification and model structure determination.

For flight test evaluation, FLIGHTLAB provides signal processing utilities. These utilities are applied to the flight test data to insure dynamic consistency, identify instrumentation errors and reconstruct unmeasured states. The utilities include:

1. **Fast Fourrier Transform**: The FFT describes the frequency content of a signal in terms of its magnitude and phase. This is often useful in isolating noise sources so as to design a filter to eliminate them.

2. **Frequency Response**: This utility uses autocorrelation and cross correlation of sensor data to construct a magnitude and phase plot versus frequency that gives insight into transfer function of selected input/output pairs, Ref. [5]. A multi-input/multi-output linear model may be constructed to be consistent with measured frequency response data to allow direct extraction of linear models from flight test data.

3. **Butterworth Filter**: This is a high order filter that produces a sharp cutoff at a specified frequency to eliminate noise while minimizing the effect on lower frequency data.

4. **Kalman Filter/Smoother**: This utility estimates the noise content of the signals based on kinematic consistency of redundant sensors and generates a statistical best estimate of the time response given the available measurements and kinematic constraints. It also reconstructs unmeasured states from kinematic consistency with measured states and identifies instrumentation errors.

5. **Integrator/Differentiator**: These utilities are used for performing preliminary consistency tests by integrating rates to compare with attitude data or differentiating rates to compare with angular accelerometer data.

Hypermedia Documentation Tool

The key feature of modern computer aided tutorials is the ability for automated navigation through the tutorial material. This feature has been demonstrated in our prototype tutorial developed in Phase I. The automated learning is accomplished with the modern documentation tool, **hypermedia**, Ref. [6]. The prototype tutorial presents its tutorial documents (text, table, and figures) utilizing **hypermedia**. **Hypermedia** is a general text-based database that includes links among documents. These links are based on key words found inside each document. For example, when

you are reading the PC tutorial document about the **Handling Qualities Tutorial** and see a reference to **Pitch (Roll) Attitude Changes** (highlighted words), you can select the **Pitch (Roll) Attitude Changes** and open a document specific to that topic. While you are reading about the **Pitch (Roll) Attitude Changes**, you see a reference to **Background Information**. By selecting that topic, you open a document dedicated to it, and so on. Depending the organization of the text grouping, you can continue this process and get deeper and deeper into the topic, or jump across the topics as new ones present themselves. The hypermedia data base is read and accessed with a tool called a **browser**. A **browser** is a utility that lets you read text and select additional references based on that text.

In the Phase I effort, we have organized the tutorial materials (specification text, tables, and figures) under HTML, the Hypertex Markup Language. The HTML is a draft Internet standard for multimedia hypertex documents and is a platform independent presentation format. But it is too simple for creating and organizing large, complex documents. Therefore, we have first developed the tutorial documents based on a more generalized markup language, SGML, Ref. [7]. The SGML is an ISO standard (ISO 8879) for describing and encoding structured text. HTML itself is also based upon SGML. The tutorial materials written in SGML, are then converted into HTML format for presentation.

Prototype Tutorial

The tutorial prototyped in Phase I was designed to integrate the presentation of flying qualities specification material including fundamental flight dynamics and control theory, handling qualities parameter evaluation, control system design and vehicle simulation into one environment. This concept has been demonstrated through the prototyped tutorial. The user can interactively perform on-line specification documentation study, simulation, flying qualities evaluation, and iterative control design.

The tutorial is written for a PC that has the capability to access FLIGHTLAB with PC X-terminal emulation. The PC is networked and communicates with the host machine where FLIGHTLAB is installed through PC Xware. The PC Xware allows users to open multi-windows for terminal emulation and provides X-windows for interactive work with FLIGHTLAB.

The organization of the handling qualities and control design tutorial is illustrated in Fig. 8. We have named the tutorial product line "FLIGHTLAB/academy". The handling qualities and control design tutorial starts with the main screen as shown in Fig. 9.

Preliminary Knowledge session presents basic mathematics, flight mechanics and control theory to prepare the users with fundamental knowledge for the tutorial. A table of contents of the **Preliminary Knowledge** is given in Appendix B.

In the main screen, a user can choose **Preliminary Knowledge** to study basic mathematics or he can directly go into the **Handling Qualities Tutorial**. Of course, he always has the chance to cross reference the preliminary knowledge when he is inside the Tutorial.

As the user proceeds to the **Handling Qualities Tutorial**, he sees the display shown in Fig. 10. From there he can choose a specific session to study. For example, he may select the **Pitch (Roll) Attitude Changes** session, Fig. 11 under the **Hover and Low Speed** topic, Fig. 12. As illustrated in Fig. 11, the user can first study the background knowledge related to the specification for **Pitch (Roll) Attitude Changes** in hover and low speed. Then he can do **Quantitative Evaluation** for a specific rotorcraft. By clicking the **Quantitative Evaluation**, he displays the screen shown in Fig. 13.

Each of the options in this display presents the user with what he needs to perform quantitative evaluations associated with this piece of the specifications. Specifically, the **Load a Model and Perform Analysis** option shows the models in the database. At this point, the user can either load in a model to perform FLIGHTLAB simulation to interactively generate the data or load in the presorted data from flight test or or simulation. The analyses in this session are to perform bandwidth, phase delay, natural frequency, and damping ratio calculation. The bandwidth and phase delay are computed with the **Bandwidth** function. The natural frequency and damping ratio are computed with the **Damping** function. These flying qualities parameter evaluation results can be plotted against the specifications from the last two selections.

Going back from here, the user can continue to practice the control system design and evaluate the impact of changes in control parameters on Handling qualities. Selecting **Control system design** displays the screen shown in Fig. 14.

As shown, the user can first perform the **Time response and Frequency response of the Nonlinear open loop model** and then linearize the model. The results for the open loop system will be saved for later comparison if the user continues with the study of the closed loop system. The **Linear Quadratic Regulator** is used as an example for the control design practice. The resulting closed loop system can be compared with open loop results to study the control system.

This basically completes one session of the tutorial. The user can always go back by clicking the **Back** icon at the top of the screen for a new tutorial session.

Conclusions and Further Efforts

The Phase I effort has successfully achieved its technical objectives through the development of a demonstration prototype tutorial. The prototype tutorial concludes that

1. A computer aided flying qualities specification tutorial can be developed on a cost effective PC with X-terminal emulation.

2. The tutorial provides users with the capability to interactively access both the comprehensive FLIGHTLAB simulation/analysis environment and an automated instructional program for flying qualities specifications.

3. The tutorial has integrated the instruction of the on-line specifications and background materials, handling qualities evaluation, flight control system design and flight test scenarios simulation in one unified environment. Thus, it has functions for both training and flying qualities analysis.

The Phase I effort of this project has prepared the background for further development of a fully operational PC based flying qualities tutorial. Under Phase II, the tutorial will be expanded to include complete coverage of handling qualities evaluation, control design, loads analysis, and flight test simulation and analysis. A detailed description of proposed Phase II efforts are presented in a separate Phase II proposal, submitted to the Navy on Jan. 27, 1995.

References

[1] Advanced Rotorcraft Technology, Inc., "Flightlab/Scope Theory Manual," June, 1993

[2] Howitt, J., "Helicopter Flying Qualities Toolbox for MATLAB - a User Guide," DRA/AS/FS/WP93, Final Draft, October 1993.

[3] "U.S. Naval Test Pilot School Flight Test Manual- Rotary Wing Performance," USNTPS-FTM-NO. 106, DEC. 31, 1987, Naval Air Test Center, Patuxent River, MD.

[4] "U.S. Naval Test Pilot School Flight Test Manual- Rotary Wing Stability and Control," USNTPS-FTM-NO. 107, June 30, 1991, Naval Air Test Center, Patuxent River, MD.

[5] Ham, J., Williams, J., Tishler, M.B.,"Frequency Domain Testing," Notes for a Training Class Given at Patuxent River, MD, April, 1994.

[6] Badgett, T. and Sandler, C.,"Welcom to ...Internet, from Mystery to Mastery," MIS Press, 1993.

[7] Goldfarb, C.F.,"The SGML Handbook," Clarendor Press, Oxford, 1990

[8] Bryson, Arthur E. Jr., "Control of Spacecraft and Aircraft," Princeton University Press, New Jersey, 1994

Appendix A Handling Qualities Analysis Control Design Scripts

This appendix lists some handling qualities analysis and control system design scripts for user's reference

Script One —Bandwidth and Phase Delay:

```
//Loading data

  disp(" Loading PUMA data ...")
  load("data/puma.dat");
  b1=b(:,3);c1=c(1,:);d1=0;

// Frequency response

  disp(" Frequency response ...")
  w = logspace(1,50,100);
  w(1)=1;
  [mag,phase]=cfreq(a,b1,c1,d1,w);

//  Bandwidth and phase delay

  disp(" Bandwidth and phase delay")
  bandwdth(w,mag,phase);

//plot
  disp(" Plot bandwidth and phase delay against ADS-33C requirement");
  [bw,pd]=bandwdth(w,mag,phase);
  plotbw(bw,pd,1);
```

Script Two — Bandwidth and Phase Delay:

```
//Impulse response
 disp(" Damping and natural frequency from impulse response...");
```

```
t=0:0.02:10;t=t';
y=impulse(a,b,c,d,3,t);
phid=y(:,1);

//Roll response Damping
[wn,zeta]=damping(t,phid);

//Plot against ADS-33C

disp(" Plot damping and frequency against ADS-33C requirement");
plotdmp(wn,zeta,1);
```

Script Three — Control system Design:

```
// load a model - OH-6A
// x = [u w q theta v r p phi]';
// u = [lng coll lat ped]';
// y = [u w v r]';
exec(''oh6a.exc'',1) // got (a,b,c,d) matrices
[no,ns] = size(c);
[ns,ni] = size(b);

// augment the system matrices with the integral-error state
a2 = [a zeros(ns,no)
      c zeros(no,no)];
b2 = [b; zeros(no,ni)];

// design a lq regulator
qc = [zeros(no,ns) eye(no)]'*[zeros(no,ns) eye(no)];
rc = eye(ni);
[kc,ec,sc] = lqr(a2,b2,qc,rc);

// closed loop system with a command input
// output = system state (u,w,q,theta,v,r,p,phi)
// input = command (steady state output)
acl = a2 - b2*kc;
bcl = [zeros(ns,no); -eye(no)];
ccl = [eye(ns+no)];
```

```
dcl = [zeros(ns+no,no)];
// simulation
ts = 1e-2;
nt = 1500;
t = (0:nt-1)'*ts;
sd = disc([acl bcl; ccl dcl],max(size(acl)),ts);
yc = ones(nt,4)*diag([10 0 0 0]);       // command
y = filp(sd,yc);

// control system history
cnt = -y*kc';

plot(''title=Forward Speed, u,ylabel=ft/sec''); plot(t,[y(:,1) yc(:,1)]);
plot(''title=Longitudinal cyclic, ylabel=.1 in''); plot(t,cnt(:,1));
```

Appendix B Preliminary Knowledge

Chapter One: Fundamentals of Linear System

1.1 Vector
1.2 Matrix
1.3 Transformation
1.4 Eigenvalues and Eigenvectors
1.5 The Cayley-Hamilton Theorem
1.6 Home Work

Chapter Two: Flight Mechanics

2.1 Equation of Motion}
- 2.1.1 Rotor Aerodynamics and Dynamics
- 2.1 2 Body Degree of Freedom
- 2.1.3 Control Derivatives
- 2.1.4 Stability Derivatives
- 2.1.5 Home Work

2.2 Trim
- 2.2.1 Steady State
- 2.2.2 Equilibrium
- 2.2.3 Home Work

2.3 Control
- 2.3.1 Control Power
- 2.3.2 Control Sensitivity
- 2.3.3 Home Work

2.4 Stability
- 2.4.1 Static Stability
- 2.4.2 Dynamic Stability
- 2.4.3 Home Work

2.5 Dynamic Response
- 2.5.1 Dynamic Signals: Pulse, Step, Doublet, Sine-Sweep
- 2.5.2 Longitudinal Dynamics
- 2.5.3 Lateral Dynamics

2.5.4 Coupled Longitudinal/Lateral Dynamics
2.5.5 Home Work

Chapter Three: Control Theory

3.1 System, System Theory and Control Theory

3.2 Classical Control Theory
3.2.1 Laplace Transform
3.2.2 System Representation
3.2.3 Transfer Function
3.2.4 Feedback
3.2.5 Analysis Methods
Routh's Criterion, Root Locus, Bode Plot, Nyquist's Stability
3.2.6 Steady State and Transient Response
Damping Ratio and Overshoot, Gain Margin, Phase Margin
3.2.7 Methods of Improving System Performance
Single Gain Adjustment and Compensation Techniques
3.2.8 Home Work

3.3 Modern Control Theory

3.3.1 State Space
3.3.2 State Equations
3.3.2.1 Continuos-Time Linear Systems
3.3.2.2 Discrete-Time Linear Systems

3.3.3 Controllability and Observability
3.3.4 Stability of Linear System
3.3.5 Nonlinear Equations and Perturbation
3.3.6 State Variables and Transfer Functions
3.3.7 Home Work

3.3.8 Control Design
3.3.8.1 Design of Linear Feedback Control
3.3.8.2 Optimal Control
3.3.8.3 H Infinity
3.3.8.4 Home Work

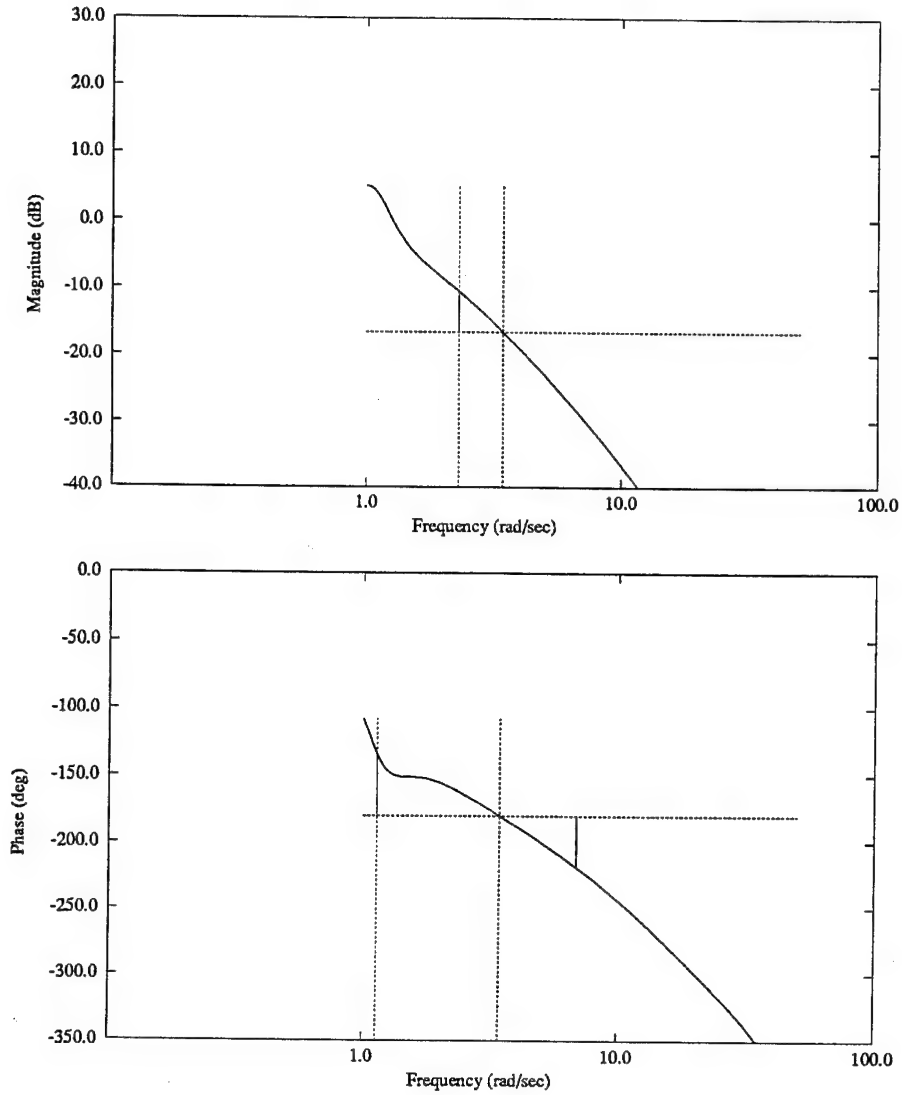

Figure 1: Bode Plot of Roll Response

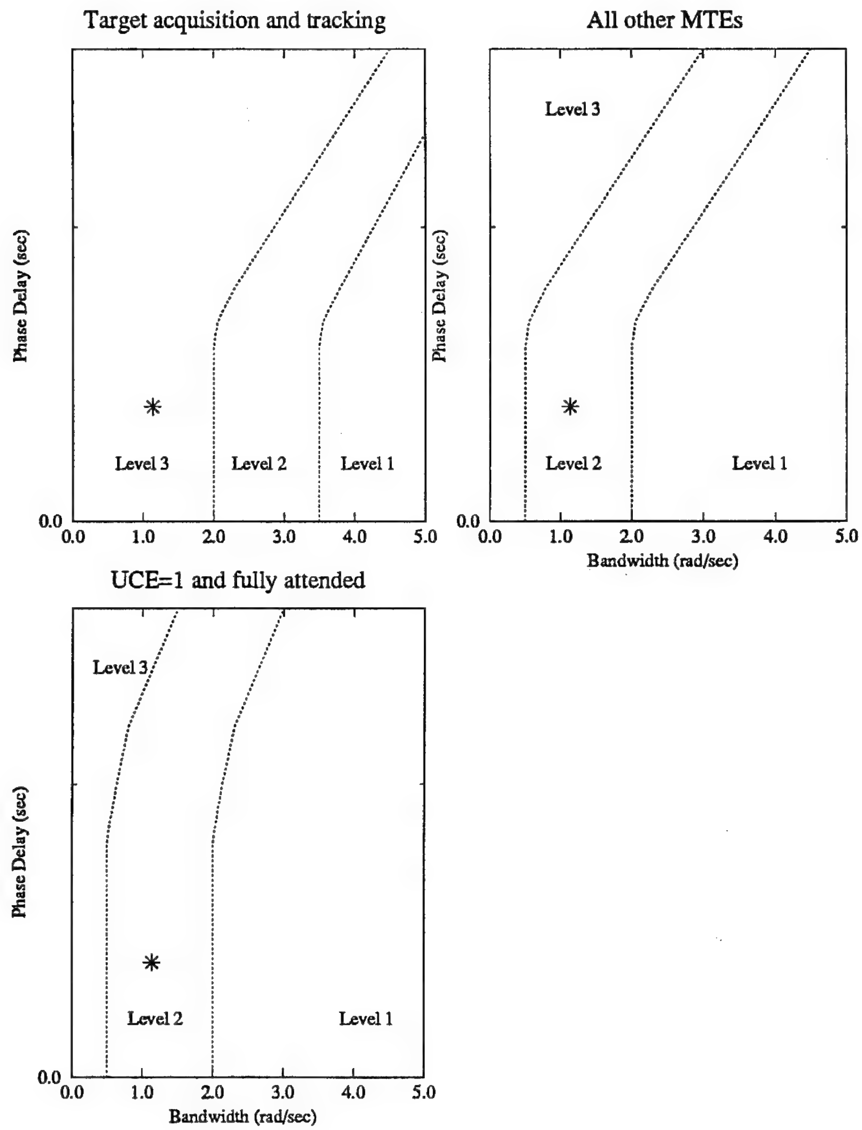

Figure 2: Bandwidth and Phase Delay against ADS-33C Requirement

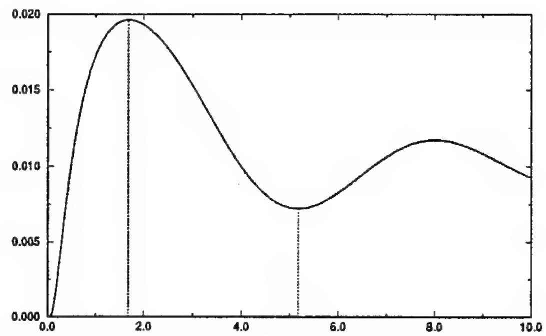

Figure 3: Time History of Roll Response

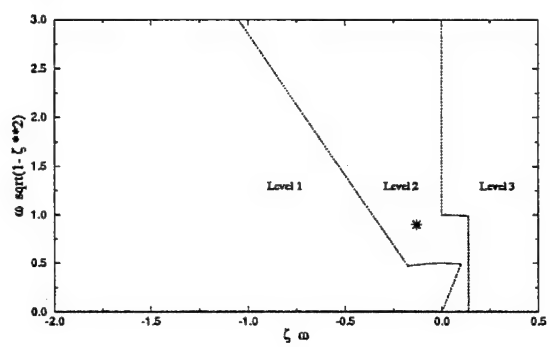

Figure 4: Damping and Frequency against ADS-33C Requirement

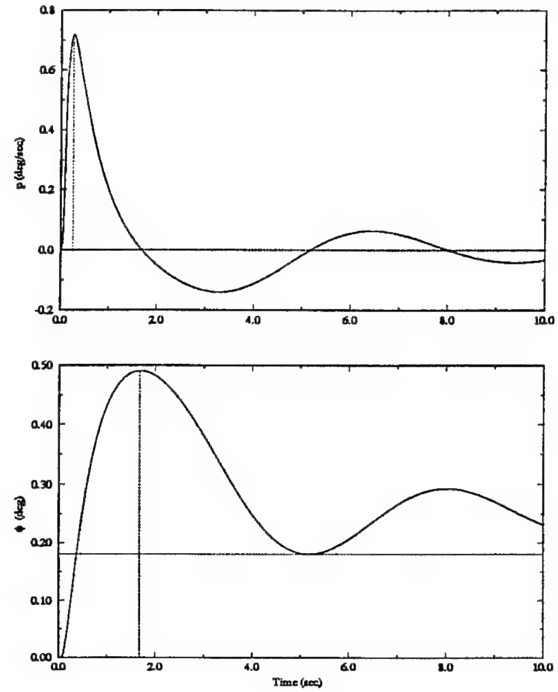

Figure 5: Time History of Roll Response (Attitude Quickness)

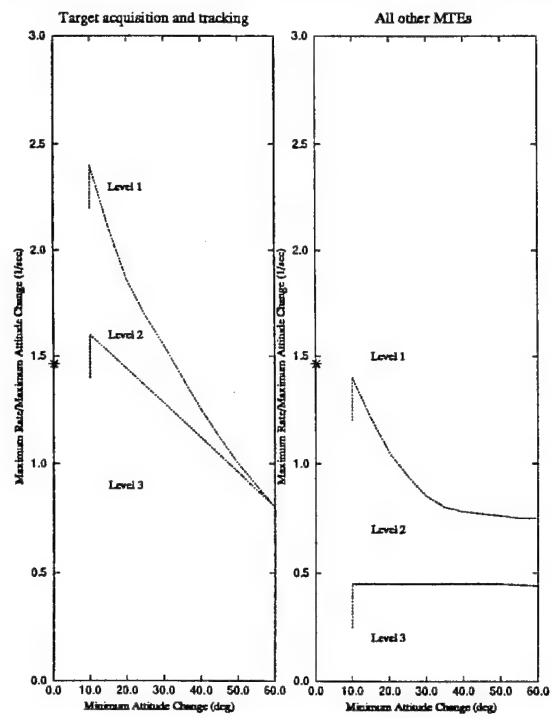

Figure 6: Attitude Quickness against ADS-33C Requirement

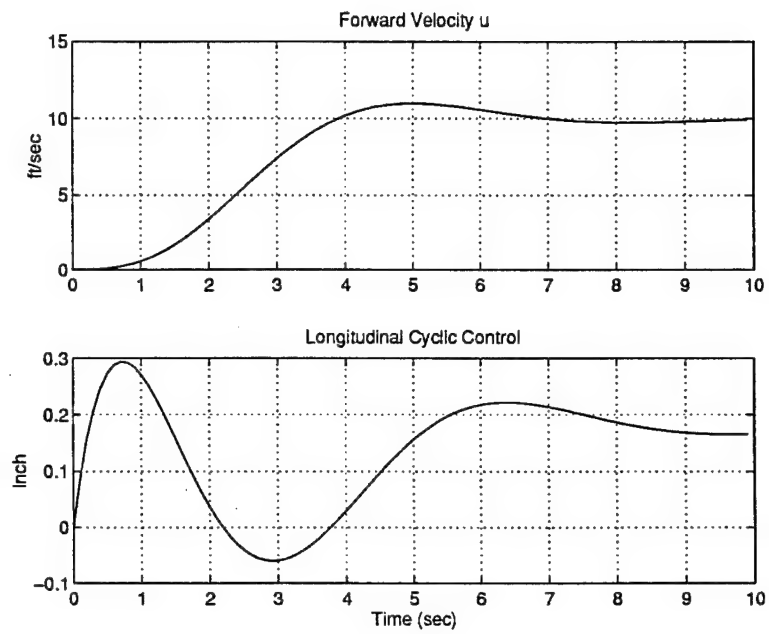

Figure 7: Forward velocity response and longitudinal input history for u = 10ft/sec command

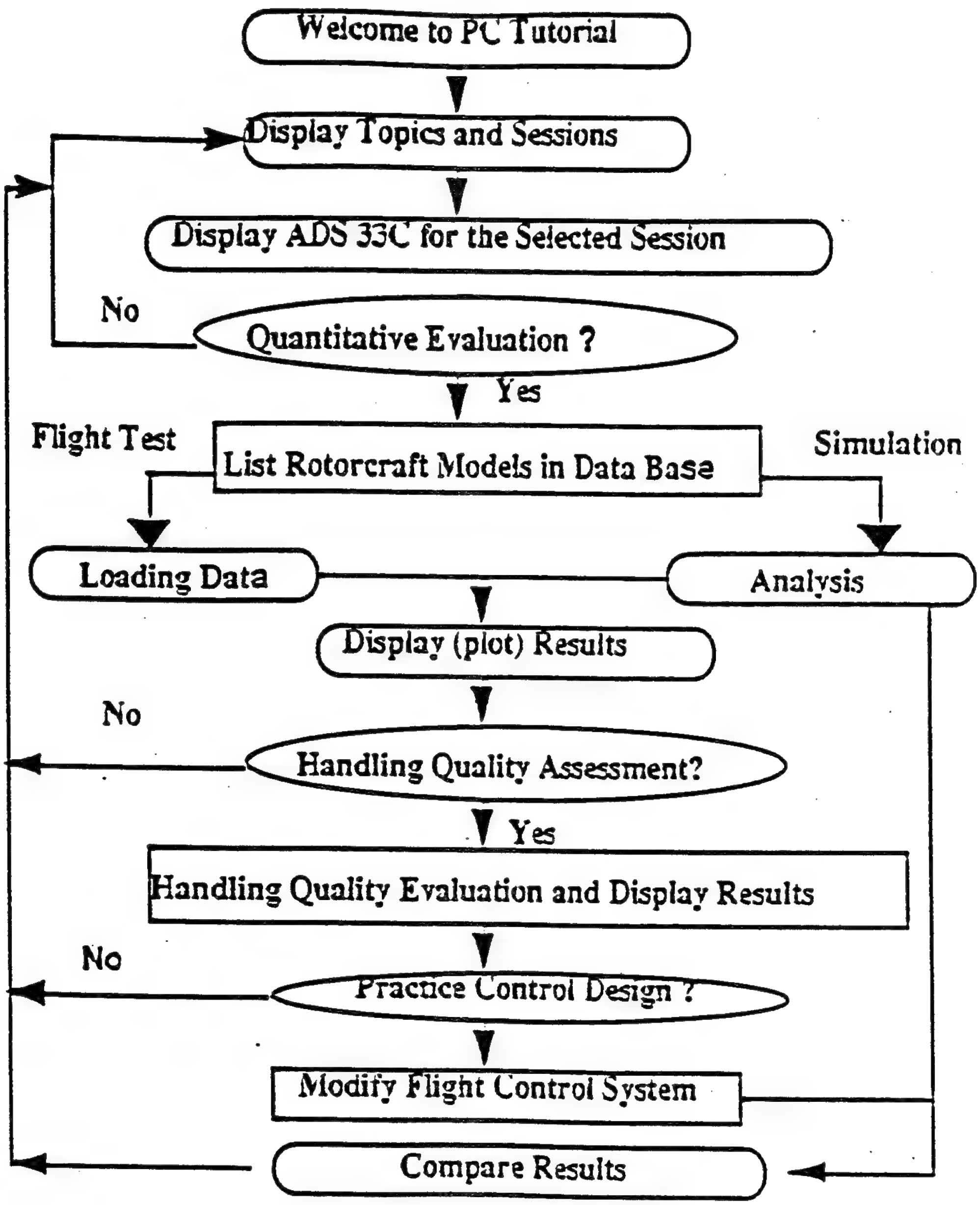

Figure 8: Organization of Tutorial

FLIGHTLAB/academy

Last updated: *Tuesday, 31 January 1995, 21:25*

- Handling Qualities Tutorial
- Preliminary Knowledge
- Specification for Handling Qualities of Military Rotorcraft
- Demo Flightlab Analysis Session
- About FLIGHTLAB/academy

Figure 9: Main Screen of Tutorial

Handling Qualities Tutorial

FLIGHTLAB/academy tutorial: preliminary demonstration.

- Scope and Definitions
  - Scope of ADS 33-C and Definitions
- Applicable Document
  - Bibliography
- General
  - General
- Required Response-Type
  - Required Response-Type
  - Character of Response-Type
- Hover and Low Speed
  - Equilibrium Characteristics
  - Pitch (Roll) Attitude Changes
  - Yaw Attitude Changes
  - Interaxis Coupling
  - Height Response to Collective Controller
  - Position Hold
  - Translational Rate Response-Type
- Forward Flight
  - Pitch Attitude Response to Longitudinal Controller
  - Flight Path Control
  - Interaxis Coupling
  - Roll attitude Response to Lateral Controller
  - Yaw Response to Yaw Controller
  - Lateral Directional Stability
  - Pitch, Roll and Yaw Response to disturbance Inputs
- Transition of a Variable Configuration Rotorcraft Between Rotor-Borne and Wing-Borne Flight
- Controller Characteristics
  - Conventional Controllers
- Specific Failures
  - Specific Failures
- Transfer Between Response-Types
  - Transfer Between Response-Types
- Ground Handling and Ditching Characteristics
  - Ground Handling and Ditching Characteristics
- Flight Test Maneuvers
  - Precision Tasks
  - Aggressive Tasks
  - Decelerating Approach to Hover

TOP: PC SBIR Tutorial

Figure 10: Handling Qualities Tutorial Screen

Handling Qualities Tutorial

Session 5.2

Pitch (Roll) Attitude Changes

Continue...

- Background information
- Quantitative Evaluation
- Control system design

Up to topic: Hover and Low Speed:
TOP: PC SBIR Tutorial

Figure 11: Pitch (Roll) Attitude Changes Screen

Handling Qualities Tutorial

Topic 5

Hover and Low Speed

The specification in this section is to insure good flying qualities for near-earth operations.

The near-earth operations are the operations sufficiently close to the ground or fixed objects on the ground, or near water and in the vicinity of ships, etc.

The small, moderate, and large-amplitude attitude changes have separate response criteria. Since the required precision of control tends to be inversely proportional to the amplitude of the attitude motion, the attitude response criteria are in terms of amplitude.

Naturally, the normal accelerations and angular rates become excessive, and control servos begin to saturate for large amplitude high-frequency motion. Thus, bandwidth is specified for small amplitude tracking only.

For moderate amplitudes, the peak angular rate changing from one steady attitude to another is specified. For large attitude, the angular rate that must be achievable is specified.

Sessions

- Equilibrium Characteristics
- Pitch (Roll) Attitude Changes
- Yaw Attitude Changes
- Interaxis Coupling
- Height Response to Collective Controller
- Position Hold
- Translational Rate Response-Type

Next topic: Forward Flight; Up: Handling Qualities Tutorial; Previous topic: Required Response-Type;
TOP: PC SBIR Tutorial

Figure 12: Hover and Low Speed Screen

Handling Qualities Tutorial

Session 5.2.B – Quantitative Evaluation

Enter analysis mode.

Continue...

- Load a model and perform analysis
- Bandwidth
- Damping
- Plot Bandwidth and Phase Delay against ADS–33C
- Plot natural frequency and damping ratio against ADS–33C

Up to topic: Pitch (Roll) Attitude Changes;
TOP: PC SBIR Tutorial

Figure 13: Quantitative Evaluation screen

Handling Qualities Tutorial

Session 5.2.C – Control system design

A control system design process will be demonstrated for a UH–60 model. The loaded model is hovering at 90 ft above sea level. This session will show how to design a linear quadratic regulator for this model in compliance with the ADS–33C requirements.

Continue...

- Characteristics of the Open–Loop System
- Linearization
- Linear Quadratic Regulator
- Closed–Loop System
- Nonlinear Closed–Loop System

Up to topic: Pitch (Roll) Attitude Changes;
TOP: PC SBIR Tutorial

Figure 14: Control System Design Screen

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